

Measurements of low-energy neutron production in (p,n) and (d,n) reactions

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Boron Neutron Capture Therapy (BNCT), a promising modality for the treatment of glioblastoma multiforme, relies on the use of high-intensity epithermal neutron beams. Although clinical trials are under way at nuclear reactors, neutron beams of superior quality and higher availability could be produced with accelerators, via suitable (p,n) or (d,n) reactions at low energy. To meet medical requirements and minimize the demands on the accelerator, in particular the beam current, one has to choose reactions characterized by large yield of low-energy neutrons ($E_n < 1$ MeV) and by little or no contamination of γ -rays and high-energy neutrons. Well known neutron sources, such as the ${}^7\text{Li}(p,n){}^7\text{Be}$ and ${}^9\text{Be}(p,n){}^9\text{B}$ reactions, are being considered for use in various accelerator-based BNCT projects. In particular, in the LBNL/UCSF proposal the use of the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction is planned at a proton energy between 2.3 and 2.5 MeV [1]. It cannot be excluded, however, that other proton- or deuteron-induced reactions could lead to a more convenient accelerator, in terms of size, costs, target cooling, etc...

We report here on the results of a systematic search of low-energy neutron sources, performed at the 88" cyclotron by a collaboration between NSD and AFRD of LBNL and Istituto Nazionale Fisica Nucleare (INFN), Bari, Italy. Neutron yield and energy spectra have been measured for (p,n) and (d,n) reactions characterized by a positive or slightly negative Q-values, and for incident energies of 1.5 and 2.5 MeV for deuteron and proton beams respectively. To minimize the scattering of neutrons from material surrounding the target, a thin-wall aluminum scattering chamber was mounted in cave 4B, at a distance of more than 2 m from walls or other heavy material. The low-energy deuteron and proton beams were obtained by accelerating D_3^+ and H_3^+ molecular beams.

Neutrons were detected by means of 5 liquid scintillator cylindrical cells, 5" diameter and 2" thick, mounted at 0, 30, 60, 90 and 140 degrees and at a distance of 50 cm from the target [2]. The threshold on the light output was kept around an estimated value of 10 keV electron equivalent, to detect neutrons of energy as low as 100 keV. A plungeble Faraday Cup was used for absolute normalization purposes. For thick targets measurements, the integrated charge on the target was also recorded, for relative normalization purposes.

Table I shows the preliminary results for the most significant (p,n) and (d,n) reactions studied (for thick targets). For comparison, the known values for the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction are also included in the table. The yield at 0 degrees, the total yield and the energy spectrum

of emitted neutrons were the main focus of the measurements. For potential application in BNCT, a reaction should be characterized by an abundant production of low-energy neutrons (< 1 MeV) and by little or no emission of high-energy neutrons and γ -rays. As clear from the table, most of the studied reactions do not meet these conditions. In particular, the ${}^9\text{Be}(d,n){}^{10}\text{B}$ reaction at 1.5 MeV, recently indicated by a group from S. Africa as a potential low-energy neutron source for BNCT [4], presents a large contamination of high energy neutrons, which would significantly worsen the quality of the epithermal neutron beam. Other reactions, such as the ${}^{12}\text{C}(d,n){}^{13}\text{N}$ at 1.5 MeV and the ${}^9\text{Be}(p,n){}^9\text{B}$ at 2.5 MeV present a clean low-energy neutron peak, but the yield is too low for the currently available accelerator technology.

Among the studied reactions, only the ${}^{13}\text{C}(d,n){}^{14}\text{N}$ reaction has features potentially interesting for application in accelerator-based BNCT. The estimated total yield is among the largest observed in d-induced reactions (see also ref. [3]), and is only ~ 5 times smaller than the $\text{Li}(p,n)$ reaction. The main peak in the neutron energy spectrum is centered at an energy of 700 keV, most probably connected to the 5.69 MeV excited state of the ${}^{14}\text{N}$ residue. A contamination of high-energy neutrons is observed at the level of 20 %, but a large fraction of this contamination is concentrated at neutron energies below 1.5 MeV, corresponding to the 5.1 MeV level of the ${}^{14}\text{N}$ residue. It should be mentioned that the ${}^{13}\text{C}(d,n)$ reaction does not present particular target cooling and radioactive waste handling problems which affect other neutron-producing reactions. More accurate measurements of this reaction, and extensive simulations of the moderation process will be needed to better judge the applicability of this reaction for accelerator-based BNCT.

Reaction	E_{in} (MeV)	Tot. Yield (n/ μC)	E_n (MeV)	$Y(E_n > 1 \text{ MeV})$ (%)
${}^7\text{Li}(p,n){}^7\text{Be}$	2.5	9.8×10^8	0.6	0
${}^9\text{Be}(p,n){}^9\text{B}$	2.5	3.9×10^7	0.4	0
${}^9\text{Be}(d,n){}^{10}\text{B}$	1.5	7.6×10^7	0.45	45
${}^{12}\text{C}(d,n){}^{13}\text{N}$	1.5	3.2×10^7	0.55	0
${}^{13}\text{C}(d,n){}^{14}\text{N}$	1.5	2.1×10^8	0.7	30

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